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A New Multilevel Active Power Filter Using Switches Meticulously Controlled

Zahzouh Zoubir*, Khochmane Lakhdar*, Haddouche Ali**
* Department of Mechanical Engineering, Faculty of Technology, 20 Aout 1955 University, Skikda, Algeria
** Departement of Electromechanical Engineering, Faculty of Technology, Badji Mokhtar University, Annaba, Algeria

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ABSTRACT

Shunt active power filter based on multilevel inverter is used to compensate the power factor and to delete the harmonics. This one permits to reduce the inverse voltages applied to the filter switches and their switching frequencies. Nevertheless, the high number of used switches requires a complicated controller and increases the switching losses; where the necessity of finding another resolution system. In this work a new topology of multilevel inverter is proposed as a shunt active power filter using two IGBT transistors in series of opposite sense meticulously controlled by a parallel control algorithm, with the concept of reduced number of six switches which are able to create five levels of the output voltage. This system substute the classical system of eight switches. The harmonic currents identification is carried out using the instantaneous active and reactive power method. The simulation is performed using Matlab/Simulink. The obtained results show that the filtering performances are well enhanced.

Corresponding Author:

Zahzouh Zoubir,
Departement de Génie Mecanique, Faculté de Technologie,
Université 20 Aout 1955-skikda,
B.P. 26, Route d'Elhadaiek, Skikda 21000, Algeria.
Email: zzahzouh@yahoo.fr

1. INTRODUCTION

The use of controlled systems, especially the power static converters based on electronic components, leads to a serious problem of disturbed currents in terms of electrical networks of distribution.

These disturbed currents engender damages in the power quality. Those explain the increase of the harmonic rate and the unbalance of both currents and voltages, and also an important consummation of the reactive power. These harmonics disturbances have catastrophic consequences on the performances of all the receivers connected to electrical networks and the supply source. So, it is necessary to find a well adapted solution permitting to decrease these disturbances at the lowest level. A shunt system of the disturbing load must be connected in order to make both the current and the voltage under sinusoidal waveform and the power factor closer to unity.

The idea of the active power filter presents a well adapted solution to these problems faced in active power lines [1]. It has known a fast development since the arrival of new electronic components (switches) such as GTO thyristors, IGCT and IGBT transistors [2]. Active filters can be structured in parallel [3], in series [4], [5] or hybrid [6], [7] in the network.

Inverters with two or three levels, have a reduced number of switches. They are also used as shunt active power filters to suppress the harmonic currents and to compensate the power factor. However, a high switching frequency is required to achieve a purely sinusoidal waveform of the supply current [8], [9]. As a result, the delay created during switches turn-on/off creates power losses, limiting the robustness of the DC/AC conversion. Furthermore, high inverse voltage applied to the switches can demolish the semiconductor characteristics. Consequently, a negative impact on the energy quality appears on the waveform of both supply voltage and current.

Multilevel inverters structures permit to reduce the problems by producing a hatched output voltage composed of many levels [10]-[12]. The use of this sort of topology helps to limit the stress in inverse voltage supported by switches via dividing the continue voltage bus DC. Each switch, in locked state, supports a part of the full continue voltage DC. The multiplication of levels permits to reduce the amplitude of each part increasing or decreasing the output voltage.

These sorts of multilevel inverters must operate with exact control algorithms to turn on/off the power switches in optimal time. The algorithm permits also to suppress some higher order harmonics, and consequently, to improve the output current and voltage frequency spectrums [13], [14]. Nevertheless, the number of semiconductors can be higher; it requires a very complex controller that engenders switching losses of each switch. This can have a negative impact on the robustness of the multilevel inverter.

Several techniques are used to detect disturbances in the electrical networks. Frequency detection techniques are carried out by the Discrete Fourier Transform (DFT) which can be used to analyze the voltage or current non-sinusoidal signals. Fast Fourier Transform (FFT) and Discrete Recursive (TFDR) [15], [16] represent well efficient computational methods. However, the direct application of these methods requires a significant computation time which delays the filter control response. Nevertheless, there are other techniques, such as Notch filter [17]. The Artificial Neuron Network (ANN) technique has been developed to the optimal identification of the harmonic signals [18], [19] and the instantaneous power method [20],[21] which is the constantly used one.

Current studies are focused on the determination of a robust control strategy for different filter topologies, such as sliding mode technique [22]. Pulse Width Modulation (PWM) control technique applied for multi–level and the Fuzzy controller [23], [24] are able to create the logic signals which are sent to the electronic components. Hysteresis [25] or three-dimensional space vector modulation [26] can also be used to control the inverters.

In this paper, a new topology of five-level inverter using two IGBT transistors in series of opposite sense meticulously controlled by a parallel control algorithm, is proposed as a shunt active power filter (SAPF). This topology has a small number of power switches (six IGBT transistors + zero Diodes for neutral point clamped) able to generate five levels of output voltage. Classical systems of the NPC inverter require eight power switches (eight IGBT transistors + zero Diodes for neutral point clamped).

It can improve the filtering performances and answer better to the industrial requirements [27]-[30]. It can also minimize the power losses in the inverter by a reduced number of switching pulses. This filter permits to maintain the switch characteristics by reducing the inverse voltage applied to semiconductors.

The identification of these harmonic currents is made with the instantaneous active and reactive power method. These techniques make the supply current under the sinusoidal waveform with a power factor closer to unity. The control of the filter switches is made by a PDPWM (phase disposition Pulse Width Modulation) operating with four triangular carriers of low switching frequency equal to 5000 Hz in the first time and equal to 15000 Hz in the second Time in order to eliminate the ripples appearing on the current waveform (high frequency distortions). We are also, interested to regulate the injected current by using the fuzzy-controller technique. The numerical simulation is developed and performed by using Matlab/Simulink. The obtained results show that the proposed 5L-SAPF with two switches in series of opposite sense improves the filtering performances. This improvement in the first or in the second time (5000&15000 Hz) shows a reduction of the total harmonic distortions of the currents (THD<5%) conform to the permissible limits in accordance to IEEE norms [31]. The proposed system made the supply current under a sinusoidal waveform and in phase with the supply voltage. Furthermore, the three phase voltages have the same amplitudes, sinusoidal waveforms and phases balance.

2. SYSTEM PROCESSED DESCRIPTION

Figure 1 shows the new topology of the multilevel inverter connected to the three-phase electrical network. It is composed of three identical structures which operate independently at each phase.

In a single phase each structure is composed of two capacities C_1 and C_2 and six bipolar switches *Sw1, Sw2, Sw3, Sw4, Sw5* and *Sw6* (Figure 2). The two first are meticulously controlled, connected in anti-series between the points *O* (center of the C_1 and C_2) and *n* (neutral). They generate the voltage levels $V_{dc}/2$, 0, $-V_{dc}/2$ and ensure the bidirectional for the current and the voltage across the ground and the middle of the DC bus. To generate the 5 levels of the output voltage $-V_{dc}$, $-V_{dc}/2$, 0, $+V_{dc}/2$, $+V_{dc}$, we have chosen to dispose two capacitors (C_1, C_2), that ensure a continuous supply of the DC bus, each one has an amplitude equal to $V_{dc}/2$.

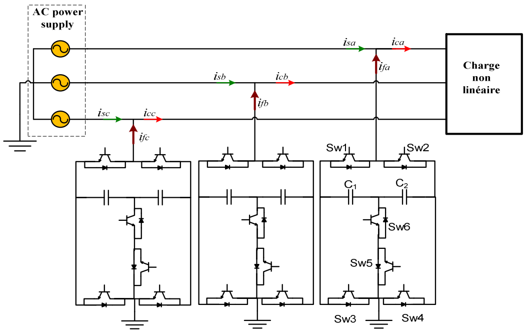

Figure 1. New 5L-SAPF linked at the electrical network

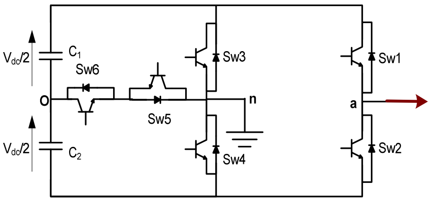

Figure 2. Modified model for a single phase

The states of opening and closing for all SAPF switches of this new topology are summarized in Table 1.

Table 1. Switching table for proposed system

Sw1	*Sw2*	*Sw3*	*Sw4*	*Sw5=Sw6*	*van*
1	0	0	1	0	V_{dc}
1	0	0	0	1	$V_{dc}/2$
1	0	1	0	0	*0*
0	1	0	0	1	$-V_{dc}/2$
0	1	1	0	0	$-V_{dc}$

3. INSTANTANEOUS ACTIVE AND REACTIVE POWER IDENTIFICATION METHOD

The three phase voltages and currents values instantaneous in *α-β* space can be expressed by:

$$\begin{bmatrix} v_0 \\ v_\propto \\ v_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 1 & \frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} v_{an} \\ v_{bn} \\ v_{cn} \end{bmatrix} \tag{1}$$

$$\begin{bmatrix} I_0 \\ I_\propto \\ I_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 1 & \frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} I_{ca} \\ I_{cb} \\ I_{cc} \end{bmatrix} \tag{2}$$

The instantaneous active and reactive powers in this space are calculated by:

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} v_\propto & v_\beta \\ -v_\beta & v_\propto \end{bmatrix} \begin{bmatrix} I_\propto \\ I_\beta \end{bmatrix} = \begin{bmatrix} \bar{p} + \tilde{p} \\ \bar{q} + \tilde{q} \end{bmatrix} \tag{3}$$

From the expression (3), we have:

$$\begin{bmatrix} I_\propto \\ I_\beta \end{bmatrix} = \frac{1}{v_\alpha^2 + v_\beta^2} \begin{bmatrix} v_\propto & -v_\beta \\ v_\beta & v_\propto \end{bmatrix} \begin{bmatrix} \bar{p} + \tilde{p} \\ \bar{q} + \tilde{q} \end{bmatrix} \tag{4}$$

To extract the reference currents expression in function of instantaneous power in the α-β space, this is given by:

$$\begin{bmatrix} I_\propto \\ I_\beta \end{bmatrix} = \frac{1}{v_\alpha^2 + v_\beta^2} \begin{bmatrix} v_\propto & -v_\beta \\ v_\beta & v_\propto \end{bmatrix} \begin{bmatrix} \bar{p} \\ 0 \end{bmatrix} + \frac{1}{v_\alpha^2 + v_\beta^2} \begin{bmatrix} v_\propto & -v_\beta \\ v_\beta & v_\propto \end{bmatrix} \begin{bmatrix} 0 \\ \bar{q} \end{bmatrix} + \frac{1}{v_\alpha^2 + v_\beta^2} \begin{bmatrix} v_\propto & -v_\beta \\ v_\beta & v_\propto \end{bmatrix} \begin{bmatrix} \tilde{p} \\ \tilde{q} \end{bmatrix} \tag{5}$$

To compensate the reactive power and harmonic currents generated by the nonlinear load simultaneously, the reference currents must include $\tilde{p}, \bar{q}$ and $\tilde{q}$ as followings:

$$\begin{bmatrix}\tilde{I}_\propto \\ \tilde{I}_\beta\end{bmatrix} = \frac{1}{v_\alpha^2+v_\beta^2}\begin{bmatrix}v_\propto & -v_\beta \\ v_\beta & v_\propto\end{bmatrix}\begin{bmatrix}0 \\ \bar{q}\end{bmatrix} + \frac{1}{v_\alpha^2+v_\beta^2}\begin{bmatrix}v_\propto & -v_\beta \\ v_\beta & v_\propto\end{bmatrix}\begin{bmatrix}\tilde{p} \\ \tilde{q}\end{bmatrix} = \frac{1}{v_\alpha^2+v_\beta^2}\begin{bmatrix}v_\propto & -v_\beta \\ v_\beta & v_\propto\end{bmatrix}\begin{bmatrix}\tilde{p} \\ q\end{bmatrix} \tag{6}$$

The reference currents in the a-b-c space are given by:

$$\begin{bmatrix}I_{ref1} \\ I_{ref2} \\ I_{ref3}\end{bmatrix} = \sqrt{\frac{2}{3}}\begin{bmatrix}1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2}\end{bmatrix}\begin{bmatrix}\tilde{I}_\propto \\ \tilde{I}_\beta\end{bmatrix} \tag{7}$$

The model of the instantaneous powers method has been implemented in Matlab / Simulink to extract the reference currents of the Equation (7) shown in Figure 3.

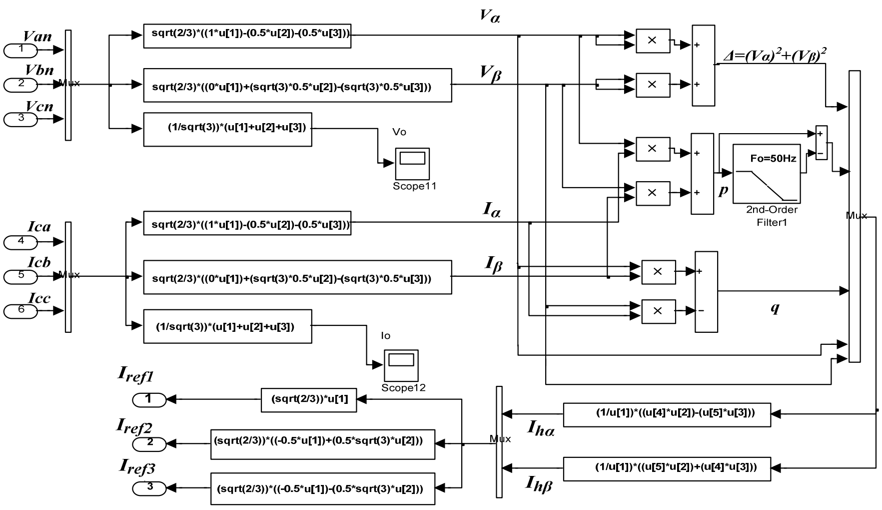

Figure 3. Algorithm for extraction of reference currents in Matlab/simulink

4. CONTROL STRATEGY

The injected harmonic current by the SAPF is obtained through the control of IGBT switches. This is achieved by the phase disposition pulse width modulation (PDPWM), this technique is mainly based on the comparison between the reference current signal (I_{ref}) and the four identical triangular carriers (U_{p1}, U_{p2}, U_{p3}, U_{p4}) as shown in Figure 4. This one sends 6 logical signals simultaneously, 0 or 1 for each one; transmited to the switches (*Sw1*, *Sw2*, *Sw3*, *Sw4*, *Sw5*, *and Sw6*).

The two carriers U_{p1} and U_{p2} allow generating the levels V_{dc} and $V_{dc}/2$ respectively. By symmetry, the levels $-V_{dc}/2$ and $-V_{dc}$ are created by the carriers U_{p3} and U_{p4} respectively. The level $V_{dc}=0$ is obtained when the reference signal is located between the carriers U_{p2} and U_{p3}.

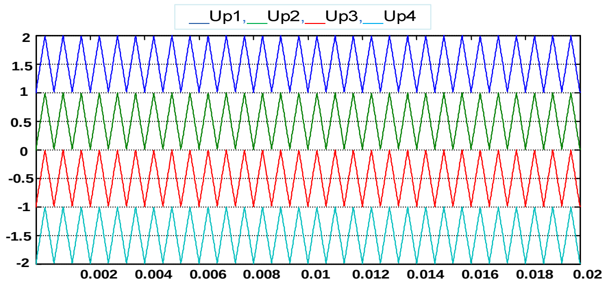

Figure 4. Phase Disposition *PWM* with four identical Triangular Carriers

The simulation model explains in detail the control of the switches (Figure 5), the new parallel algorithm makes simultaneously the comparison between I_{ref} with 4 carriers, and this method can quickly generate the signals sent to the switches of the proposed model at the right time.

5 levels of the SAPF output voltage (V_{an}) respect 5 conditions performed simultaneously (in parallel) as follows:

a. If $Iref \geq U_{p1}$, $Sw1=1$, $Sw2=0$, $Sw3=0$, $Sw4=1$, $Sw5=0$, $Sw6=0$ & $v_{an}=v_{dc}$.
b. If $U_{p1} > Iref \geq U_{p2}$, $Sw1=1$, $Sw2=0$, $Sw3=0$, $Sw4=0$, $Sw5=1$, $Sw6=1$ & $v_{an}=v_{dc}/2$.
c. If $U_{p2} > Iref \geq U_{p3}$, $Sw1=1$, $Sw2=0$, $Sw3=1$, $Sw4=0$, $Sw5=0$, $Sw6=0$ & $v_{an}=0$.
d. If $U_{p3} > Iref \geq U_{p4}$, $Sw1=0$, $Sw2=1$, $Sw3=0$, $Sw4=0$, $Sw5=1$, $Sw6=1$ & $v_{an}=-v_{dc}/2$.
e. If $U_{p4} > Iref$, $Sw1=0$, $Sw2=1$, $Sw3=1$, $Sw4=0$, $Sw5=0$, $Sw6=0$ & $v_{an}=v_{dc}$.

5. FUZZY-CONTROLLER APPLICATION

To inject an optimal harmonic current by the proposed model, the fuzzy logic controller was chosen to regulate the switches control signals through the parallel control algorithm. In this work, a model established in Matlab/Simulink is shown in Figure 6. The operation here consists to replace the classical PI regulator by a fuzzy controller. This technique allows correcting the error between the reference current (I_{ref}) and the injected one (I_{inj}). The error and its derivative are defined by three sub-sets**:** negative *N*, zero *ZE* and positive *P*, knowing that the membership functions are Gaussian type. The output signal C_{de} depends on the input states defined by five sub-sets, large negative *LN*, negative *N*, zero ZE, positive *P* and large positive *LP*. In this case, the membership functions are triangular type. Fuzzy controller should follow the fuzzification steps that use the "minimum" operator, and the inference mechanism that contains five rules. Finally by the help of the defuzzification of the fuzzy output, the barycentric method is applied. Fuzzy rules are based on the error variation sense (*e*), the algebraic sign, as well as its derivative "*de/dt*". So, the controller $C_{de,}$ will be given according to the following state conditions:

1. If *e* is *ZE* then C_{de} is *ZE*
2. If *e* is *P*, then C_{de} is *LP*
3. If *e* is *N*, then C_{de} is *LN*
4. If *e* is *ZE* and "*de/dt*" is *P*, then C_{de} is *N*
5. If *e* is *ZE* and "*de/dt*" is *N*, then C_{de} is *P*

After having the corrected signal (C_{de}) at the bloc output of the fuzzy controller, it will be intersected with the four triangular carriers to generate logic signals sent to the IGBT switches of the proposed model.

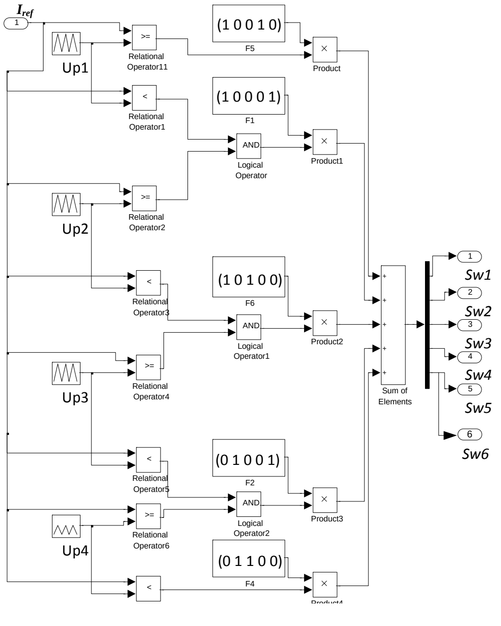

Figure 5. Logical signals of parallel control algorithm

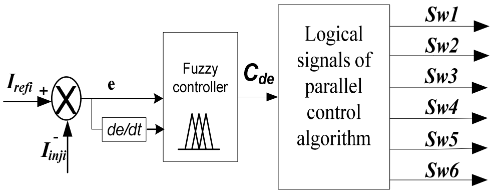

Figure 6. Scheme bloc of fuzzy controller

6. SIZING OF THE DC BUS CAPACITORS

An approach has been proposed in the literature [32], to size capacitors that feed the active filter. The transient variations in the instantaneous power absorbed by the load engender fluctuations in voltage V_{dc} across the capacitors. The amplitude of these fluctuations can be controlled by a judicious choice of the equivalent capacity value C which is expressed by $C = (12.I_{FA})/(\Delta V_{dc}.\pi.\omega_s)$. I_{FA} is the maximum amplitude of the injected current. ΔV_{dc} is the fluctuation equal to 5% of Vdc. f_s is the switching frequency of the carriers ($\omega_s = 2.\pi.f_s$). In this case, $I_{FA} = 40$ A with I_{FA} (presented in the results), $V_{dc} = 1000$ V, $\Delta V_{dc} = 5\%$. V_{dc}, $f_s = 15$ kHz, C will equal to $32.42\ \mu F$; then: $C_1 = C_2 = 2.C = 64.84 \mu F$,Because C_1 and C_2 are connected in series.

7. DC VOLTAGE REGULATION OF THE ACTIVE FILTER

Regulating the DC bus voltage of the proposed system can be improved by adjusting the small rate of active power in capacitors. Thus, it compensates the losses by conduction and switching [33], [34]. The regulation loop of the voltage is designated to be smaller than the current loop. The regulation circuit of the DC voltage must be fast and that answer only for the steady state conditions. Transient variations in the DC voltage are not permitted and are taken into consideration when selecting the appropriate value of the capacitor. From the steady state, the fundamental component is not included in the reference current. For that, a regulator of a low-pass first order filter is required to maintain DC voltage (V_{dc}) closer to the DC voltage reference ($V_{dc\text{-ref}}$), the transfer function can be written as following:

$$G_c(s) = \frac{K_c}{1+\tau_c.s} \tag{8}$$

With: K_c, τ_c gain and time constant of the low pass filter

The regulation loop of the DC voltage is expressed by the following transfer function:

$$\frac{V_{dc}}{V_{dc-ref}} = \frac{K_c}{\tau_c.C.V_{dc-ref}.s^2 + C.V_{dc-ref}.s + K_c} \tag{9}$$

8. MODEL AND SIMULATION PARAMETERS

For this simulation, a three phase diode bridge rectifier with RL load is used as the nonlinear load in this work. Table 2 summarizes the simulation parameters. The study is done only in the phase *a*, knowing that the two other phases (*b* and *c)* are delayed respectively by 120° and 240° relatively to the phase *a*.

Table 2. Simulation Parameters

Variable	Values
Source voltage , inductance line, frequency	$V_s = 220\ V$, $L_s = 3.10^{-4} H$, $F = 50\ Hz$
Non-linear load (Graëtz bridge 6 diodes + resistance + inductance)	$R = 4\Omega$, $L = 0.001H$
Capacitors voltage of multilevel inverter	$C_1 = C_2 = 64{,}84 . 10^{-6}\ F$
Reference Continuous supply DC bus	$V_{dc\text{-}ref}/2 = 500\ V$
Inductance at output of the active filter	$L_f = 1{,}2 . 10^{-3}\ H$

9. RESULTS AND DISCUSSION

9.1. Before Filtering

Figure 7 shows the supply voltage with the source current and its harmonic currents spectrum before filtering.

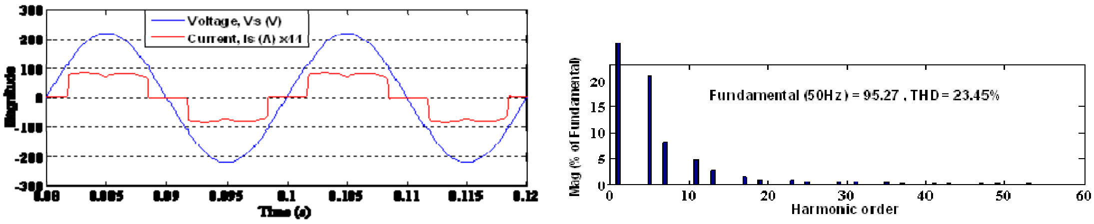

Figure 7. Supply current and voltage waveforms and its harmonic currents spectrum before filtering

The supply current obtained before filtering is completely distorted and its current Harmonic Distortion (*THD*) is *23.45*%. This value is higher than the international standard (*THD*<*5*%).

9.2. After Filtering

The simulation was made for two different frequencies of the triangular carriers

9.2.1. Results for $f_s=100.f$

SAPF using two Transistors in series Clamped into Five-level Inverter is simulated in MATLAB/SIMULINK and the output voltage waveform obtained between the neutral ‘‘*n*’’ and the phase ‘‘*a*’’ is shown in Figure 8.

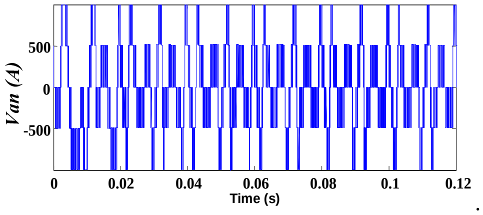

Figure 8. Output voltage waveform *Van*

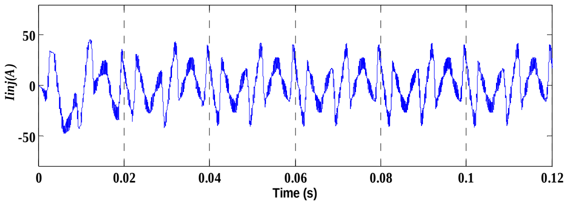

Figure 9. Active filter current with low switching frequency

The filter injected current; the supply current sinusoidal waveform and its *THD* equal to 4.41% are shown in Figure 9 and Figure 10.

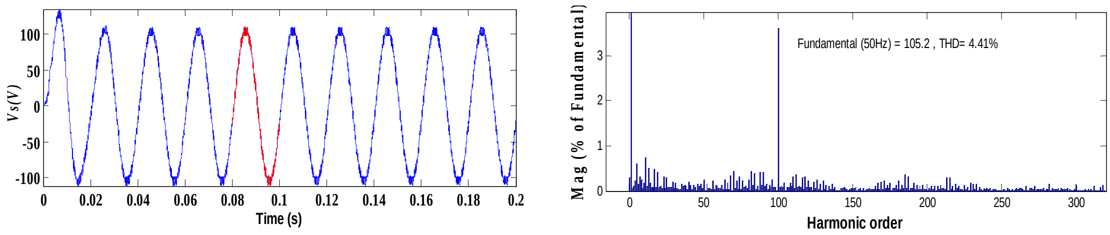

Figure 10. Supply current and its harmonic spectrum after filtering with low switching frequency (5KHz)

9.2.2. Results for $fs=300.f$

After simulation, with this high carrier frequency (15 KHz), the filter injected current; sinusoidal waveform of the supply current and its *THD* equal to 2.19% are shown in Figure 11 and Figure 12. These Figures show that the filtering performances of the proposed system are improved with a power factor closer to unity (Figure 13).

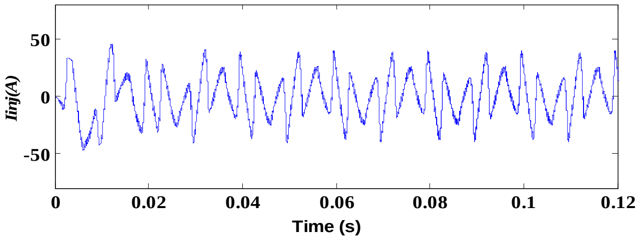

Figure 11. Active filter current with high switching frequency

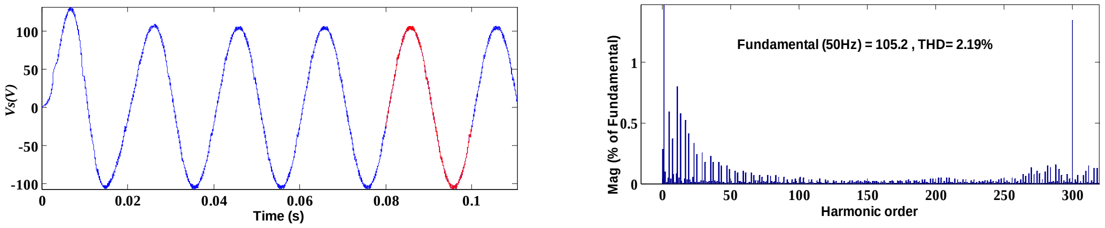

Figure 12. Supply current and its harmonic spectrum after filtering with high switching frequency (15KHz)

At the steady state, Figure 14 illustrates the supply currents which have sinusoidal waveforms with balanced phases a, b and c. Furthermore, the waveforms have the same amplitudes with the same frequencies.

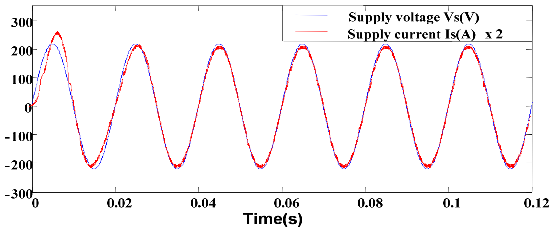

Figure 13. Power factor

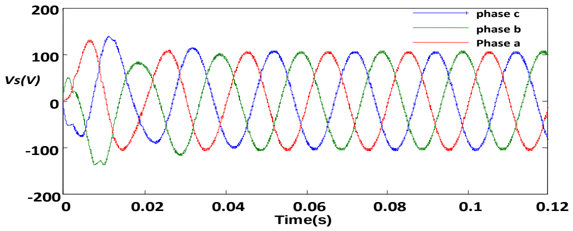

Figure 14. 3-phase waveforms of the supply currents after filtering

During the application of the modulator PDPWM, the switching frequency is imposed by the triangular carriers. Indeed, the sum of the switching frequencies of the four switches SW1, SW2, SW3, SW4 is equal to the carrier frequency 15 kHz. Figure 15 and Figure 16 illustrate clearly the complementarities of the switches: Sw2=1-Sw1 and Sw4=1-Sw3; these two conditions protect the filtering system against the short circuit.

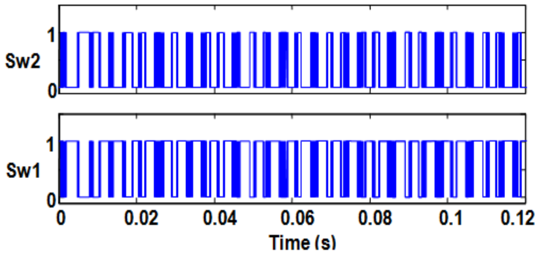

Figure 15. Switch pulses of the Sw1and Sw2

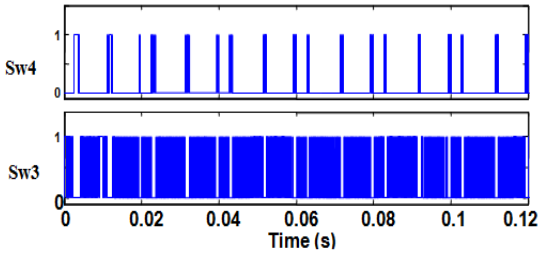

Figure 16. Switch pulses of the Sw3and Sw4

10. Conclusion

In this work, a new topology of five-level inverter with two IGBT transistors linked in series of opposite sense, meticulously controlled by a parallel control algorithm limits the harmonic currents and ensures the robustness of the converter in the electrical distribution network. The system model was implemented in Matlab/Simulink and the simulations are carried out. The results are satisfactory and conform to the permissible limits in accordance to IEEE norms. The harmonic currents identification was conducted by the instantaneous active and reactive power method as a first step. The system is controlled by PDPWM operating with four triangular carriers of switching frequency equal to 5000 Hz. On the other hand we are interested on the regulation of the injected current by using the fuzzy-controller method. The results show that the proposed filter enhances the filtering performances. It also improves the energy quality with a reduction of switching pulses. The increase of the switching frequency up to 15000 Hz eliminates some ripples appearing on the supply current waveform. A significant reduction in the total harmonic distortion rate (*THD*) is observed and calculated through FFT analysis tool in MATLAB/SIMULINK. Good compensation of the reactive power in the electrical distribution network is obtained with a power factor closer to unity.

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BIOGRAPHIES OF AUTHORS

Zoubir ZAHZOUH was born in Drean, Algeria in 1973. He received the engineer diploma and the Magister degree from the University of Annaba in electromechanical engineering in 1998 and 2001 respectively. He is actually working toward the Doctorate thesis. His area of research includes power electronics, harmonics in power systems, power quality and active harmonics filtering. Since December 2001, he is a lecturer teacher at the Department of Mechanical Engineering (Option Electromechanical) and Process Engineering, at the Faculty of Technology, University of Skikda, Algeria.

Lakhdar KHOCHMANE was born in Skikda, Algeria, 1958. He received his engineer degree and Magister degree from the University of Annaba, Algeria in 1984 and 1990 respectively, and received his Doctorate from Annaba University, Algeria 2006. He is currently a professor at department of Faculty of Technology, Mechanical Engineering (Option Electromechanical) at Skikda University. His areas of interest include power systems optimization, power quality and power systems protection and renewable energies.

Ali HADDOUCHE was born in Oued Zenati, Algeria, in 1959. He received his Phd degree from mines institute University, Moscow, USSR in 1988. Currently, he is a professor at the electromechanical department of Annaba University, Algeria. His main research interests are focused on power quality and power systems protection and renewable energies.